

Correlated Scattering and Cluster Planes

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Abstract

We suggest a new correlation in diffractive production of 2 “clusters” $A + B \rightarrow A^*B^*$ with large intrinsic angular momenta for each A^* and B^* cluster. These correlations are expected in the context of the “color dipole picture” for high energy collision and reflect the approximate conservation of dipole direction during the collision. This conservation is in particular manifest when the two dipoles, \vec{d}_A , \vec{d}_B and the impact vector \vec{b} are all parallel. The predicted positive triple correlation is between the momentum transfer $\vec{\Delta}$ and the planes of the A^* and B^* clusters.

QCD is well-tested in the short distance perturbative regime, yet it cannot predict the bulk of hadronic scattering data without additional “models” and approximations.

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Some general features of the energy dependence of cross-sections [1], and helicity conservation at high energies, trace back directly to the vectorial (spin1) nature of the gluon. The interaction with opposite sign of the latter with the quark (anti-quark) in a meson underlies the “color dipole model” of hadrons [2].

Our purpose in the following is to use the latter model and variants thereof to motivate yet another general feature of hadronic collisions, namely the tendency of the scattering plane and the planes of the final state particle clusters to be parallel.

During the short {Lorentz contracted} time of a high energy collision the $q\bar{q}$ in, say the projectile meson, are relatively frozen and we have an instantaneous, well defined dipole \vec{d} .

This observation underlies the “Color transparency” phenomenon [3] — associated with hadrons which enter the collision as small dipoles. While such hadrons can scatter effectively at large angles — in say the center of a large nucleus, the latter is almost transparent to these “point-like configurations”, which can traverse it unscathed and cause no excitation [4].

The effect we consider here is due to the direction of the color dipoles which also tends to be conserved[5].

Thus let us assume that the colliding hadrons have instantaneous dipoles \vec{d}_A, \vec{d}_B , and that at the time of collision the centers of the dipoles (Hadrons) (which move along the $\pm z$ directions), are separated by a transverse (impact parameter) \vec{b} . [We use \sim to indicate the transverse part]. We will argue that

i) the scattering will be enhanced when \vec{d}_A, \vec{d}_B and \vec{b} are parallel and ii) the hadrons in the final states will tend to align along this common conserved direction.

We will next proceed to discuss this in a variety of settings — perturbative, and others.

(a) The feature we suggest is quite obvious in a deep inelastic, large momentum transfer Δ , limit. The reaction is then dominated by one hard gluon exchange between a quark (or anti-quark) in A and a quark (or anti-quark) in B. The scattered (anti) quarks generate two jets: the “A jet” from A and the “B jet” from B. Up to corrections due to intrinsic P_T and color neutralization we expect — on essentially kinematic grounds — that both jets will align with each other. However, in this case we do not have a third indepen-

dent direction in addition to that of the two jets. Rather we may have the “wounded” forward and backward hadrons which, having each lost an (anti) quark continue, *essentially* along the initial direction. The non-trivial and not purely kinematical prediction we make here is that the slight deviation of the “wounded Hadron” forward (A-q) and the backward (B-q) jets from their initial \hat{z} directions will be — due to the pull of the kicked quark — also along the same plane defined by Δ and the transverse jets axis.

It may be difficult however to precisely separate the forward and backward “wounded” (A-q and B-q) hadron jets from the rest and verify this statement. To have a precise determination of Δ we need in principle to measure all the particles in the A^* or in the B^* cluster. On the other hand the definition of the plane A^* and B^* , just like for the case of transverse jets does not require that all the particles in the cluster will be measured.

Our suggestion is that some similar alignment feature manifests, albeit in a weaker fashion, in a large class of hadronic interactions — where much more than kinematics is required to justify it.

(b) The directions of the dipoles are not always manifest. Thus let us consider an elastic scattering of spinless hadrons $A + B \rightarrow A + B$. the collision $(\hat{z}, \underline{\Delta})$ plane is clearly well-defined and corresponds to the impact (\hat{z}, \underline{b}) plane. To see this assume we generate by an appropriate superposition an initial relative A-B state aligned along the $\phi = 0$, \hat{x} axis:

$$|\Psi_i\rangle = \sum_l C_l \sum_{m=-1}^l |\Psi_{lm}\rangle |Y_l^m(\theta, \phi)| \quad (1)$$

After the collision we will have:

$$|\Psi_{fscatt}\rangle = \sum_l C_l (e^{2i\delta_l} - 1) \sum_{m=-1}^l |\Psi_{lm}\rangle |Y_l^m(\theta, \phi)| \quad (2)$$

with the m independent phase shifts δ_e . Hence also $|\Psi_{fscatt}\rangle$ is aligned along the same $\phi = 0$ plane. Thus the scattering from the central potential conserves the initial collision plane, as expected.

Unfortunately the projection onto the spinless initial and final particles erases any information regarding the instantaneous dipole directions and no vector is available to correlate $\underline{\Delta}$ with.

(c) Let us next consider diffractive scattering where one or both of the colliding particles transforms into “clusters of fragmentation products”: $A + B \rightarrow A^* + B^*$. The distinguishing characteristic of diffractive scattering is the existence of a “rapidity gap”. It clearly separates the particles in the A^* cluster from those in the B^* cluster. Also since a color-flavor singlet system (the “Pomeron”) is exchanged between the A - A^* and B - B^* vertices, the clusters maintain the initial valence quark flavors. In the “color dipole model” the reaction can then be viewed as the scattering of the two bound states $A = q_a \bar{q}_a$, and $B = q_b \bar{q}_b$, into the excited state A^* , B^* . If the latter have sufficiently high spins S_A^* , S_B^* and hence also large orbital angular momenta between $q_a \bar{q}_a$ in the A^* rest frame, (and likewise for the relative motion of $q_b \bar{q}_b$, inside the B^* cluster), then the planes of the clusters can be well-defined. Indeed we could construct in analogy with eq. 1 “aligned states” of $q_a \bar{q}_a$ say by superimposing the $2L_A + 1$ m states of the relative quark motion. The plane of the cluster is then defined — due to $\Delta L \Delta \phi \approx 1$ uncertainties — to within $\Delta \phi \approx \frac{1}{L_{A^*}} \approx \frac{1}{S_A^*}$. If the A^* decays into two spinless hadrons then the axis of the A^* cluster is identified with the relative decay direction of these two particles in the A^* rest frame. If A^* decays into several hadrons we can reconstruct the A^* axis using appropriate “collective variables” — similar to those used in jet analyses. We will restrict ourselves to $\Delta \ll P_z$ so that while the overall scattering $\hat{\Delta}$, $P\hat{z}$ plane of the $A + B \rightarrow A^* + B^*$ reaction is well-defined, the Lorentz transformation from the overall center mass frame to the A^* (or B^*) rest frame are boosts mainly along the z axis. We can then compute, for each of the final decay particles in A^* , the scalar product $\underline{k}_{Ai} \cdot \hat{\Delta}^i, i = 1, \dots, n_A$. to avoid the kinematical biasing due to $\sum \underline{k}_{Ai} \equiv \hat{\Delta}$ we modify it to:

$$f_i^A = \left(\underline{k}_{Ai} - \frac{\hat{\Delta}}{n_A} \right) \cdot \hat{\Delta} \quad (3)$$

The claim we are making then is that:

$$|\cos \theta_i^A| = \frac{(f_i^A)}{\left| \hat{\Delta} \right| \left| \left(\underline{k}_{Ai} - \frac{\hat{\Delta}}{n_A} \right) \right|} \quad i = 1, \dots, n_A \quad (4)$$

are *not* uniformly distributed in the 1–0 interval but are more concentrated

near unity. [And likewise for the similarly-defined $|\cos\theta_j^B|$ $j = 1, \dots, n_B$.] Let us next motivate the above dynamical correlation.

(c₁) Let us consider first the case when the impact parameter between the initial spinless particles $b = |\underline{b}|$ is larger than typical hadronic sizes.

In analogy with the Van-der-Waals-interactions in Q.E.D. we can assume that the initial unpolarized particles produce — via mutual interactions — dipole moments in each other. At say $t = 0$, we assume that the initial colliding particles are at $z = 0$, the point of nearest approach. The mutual forces will at this point be predominantly along the direction of \underline{b} , and the induced dipoles \vec{d}_A and \vec{d}_B will also align with it. Conversely let us assume that we have at $t = 0$ some dipoles \vec{d}_A and \vec{d}_B . The color analogue of the electromagnetic dipole interaction is approximated to be:

$$V_{dd}(E.M.) \approx \frac{\vec{d}_A \cdot \vec{d}_B}{r^3} - \frac{3(\vec{d}_A \vec{r})(\vec{d}_B \vec{r})}{r^5} \quad (5)$$

with $\vec{r} = \vec{b} + z\hat{e}_z$ the instantaneous separation between the dipoles. This interaction is clearly maximal if \vec{d}_A, \vec{d}_B and \underline{b} are all aligned. The large classical interactions are reflected quantum mechanically in stronger scattering probability. Hence we expect a positive correlation between the directions of \vec{d}_A, \vec{d}_B and \underline{b} . Since the latter is in the direction of $\underline{\Delta}$ we have then a \vec{d}_A, \vec{d}_B and $\underline{\Delta}$ positive correlation.

(c₂) The tendency of \vec{d}_A and \vec{d}_B to be parallel persists also in the opposite limit i.e. when $\underline{b} = 0$ and the hadrons strongly overlap.

Let us assume that the initial hadrons A and B have similar chromoelectric fields $\vec{E}_A(\vec{r})$ and $\vec{E}_B(\vec{r})$ with \vec{r} referring to the centers of A and B , in the first and second case, respectively.

Note that we do not necessarily assume that \vec{E}_A and/or \vec{E}_B have the perturbative dipole form. Rather we can incorporate various non-perturbative features by assuming that \vec{E}_A and \vec{E}_B correspond — say — in the case of large $q_a \bar{q}_a$ (or $q_b \bar{q}_b$) separation — to a confined color flux tube configurations.

In a perturbative-impulse treatment of the collision process itself we approximate the interaction by the mutual chromoelectric energy [6].

$$V_{\text{int}} \approx \int \vec{E}_A(\vec{r}) \cdot \vec{E}_B(\vec{r}) d\vec{r} \quad (6)$$

Clearly the above overlap integral (at $t = 0$, $b = 0$) is maximized when the \vec{E}_A and \vec{E}_B configurations are “parallel” both in the internal color space (Apposteriori — justifying the Abelian — Q.E.D. like approximation adopted here) and in real space i.e. when the dipoles and/or flux tubes of A and B are parallel.

(c₃) Let the quark q_a and anti-quark \bar{q}_a be in some instantaneous color field \vec{E} (due say to the other particle B , (B^*)). The sum of the forces acting on q_a and \bar{q}_a imparts the overall momentum transfer, Δ to the A^* cluster. The difference of the forces tends to separate q_a and \bar{q}_a from each other and thus to induce the \vec{d}_A dipole. {For uniform \vec{E} fields only the latter effect is operative.} The same force difference generates a relative momentum between q_a and \bar{q}_a and cause the ensuing stretching and excitation from m_A to m_A^* . As the quarks q_a and \bar{q}_a recede from each other we expect — from the electric fluxtube model for multi-particle production [7] — (which underlies the Lund model [8]) that the hadrons formed via the Schwinger mechanism in this field, will align along the tubes, i.e. the \vec{d}_A axis. There is of course a “transverse” scatter of order Λ_{QCD} relative to this axis, but, to the extent that $M_A^* \gg \Lambda_{QCD}$, it will not destroy the basic feature of \vec{d}_A and \vec{k}_i alignment. This provides then another key element in our chain of arguments by correlating the axes of the A^* cluster with \vec{d}_A (and likewise for B).

We should emphasize that we need not use specific variants of the color flux tube (or lund) models. Rather we appeal to the general “jet-like” fragmentation of the $q\bar{q}$ system with limited small momentum in the directions transverse to the jet axis.

Also note that the A - B interactions which generate the dipoles (and cause also the momentum transfer Δ) need not be perturbative one gluon exchanges. Rather we could have the dipoles and the relative separation of the $q\bar{q}$ — as well as the overall Δ — be built via many soft “eikonal-like” interactions. This corresponds to solving for the quark propagators in a background gluon field (as is done in order to derive the Schwinger formula for $q\bar{q}$ pairs production).

(d) Finally we note that whereas mutual torques may in general tend to rotate the dipoles during the collision this in *not* the case in the stationary special case of interest with $\vec{d}_a || \vec{d}_b || \hat{b}$.

If the initial particles are polarized photons or nucleons there could *a priori* be further correlations involving — in addition to the scattering and “cluster” planes — also the initial polarization.

Thus let us have a transversely polarized photon diffractively scatter into a ρ or ϕ vector meson which then decay into $\pi^+\pi^-$ or K^+K^- . The decay plane does indeed tend to correlate with the initial plane of polarization. This is however simply explained by helicity conservation/independence of the high energy process. The photo-produced ρ or ϕ have the same transverse polarization as the initial photon, and the decay amplitude $\hat{e}_V(\vec{k}_1 - \vec{k}_2)$ generates final state pseudoscalar with relative direction \tilde{n} having a $\cos^2\theta$ distribution relative to \hat{e}_V . However the ρ , ω , and φ are the 3S analogs of spin $^1S\pi$ and the $\eta\eta'$. Hence the quarks in ρ , ω , φ have to lowest order no orbital angular momentum and we do not expect the dipoles to correlate with \hat{e}_V or the scattering plane. To see the effect of interest here we need, unfortunately, to produce higher L excitations.

We have not made quantitative predictions for the magnitude of the correlations suggested here. We believe however that the extreme generality and relative model independence of these make them yet another most valuable general test of Q.C.D., which can be readily applied to a wealth of existing and future data.

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References

- [1] F.E. Low, Phys. Rev. **D12**, 163 (1975).
S. Nussinov, Phys. Rev. Lett. **34**, 1286 (1975) and Phys. Rev. **D14**, 246 (1976).
- [2] Zhong Chen and A.H. Mueller, Nucl. Phys. **B451**, 579–604 (1995).
- [3] L. Frankfurt, G. A. Miller and M. Strikman, Comm. Nucl. Part. Phys. **21**, 1–40 (1992).

- [4] Glenns R. Farrar, Leonid L. Frankfurt and Mark I. Strikman, Phys. Rev. Lett. **64**, 2996-2998 (1990).
- [5] S. Nussinov and J. Szwed, Phys. Lett. **B84**, 945 (1979).
- [6] S. Nussinov, Phys. Rev. **D50**, 3167 (1994).
- [7] A. Casher, H. Neuberger and S. Nussinov, Phys. Rev. **D20**, 179 (1979).
- [8] B. Anderson *et al.*, Phys. Rep. **97**, 31 (1983).